Influence of Moisture Content of Softwood on Liquid Penetration

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林　昭三*，貴島恒夫*：液体浸透に対する針葉樹材含水率の影響

Penetration of water or chemicals into wood which is one of the porous and penetrable materials, has an important connection with treatments for preserving, drying, pulp and paper making, or even for gluing or coating of wood.

In general, velocity of penetration is related with differences of given pressure or concentration of liquid, nature of wood especially of its microscopic structure, and moisture content of wood. STAMM[1] suggested a theoretical equation for the rate of capillary rise as follows:

$$h^2 = \frac{r\sigma t}{2\eta} \quad \cdots\cdots\cdots\cdots(1)$$

h: penetration length.
r: capillary radius.
σ: surface tension of liquid.
t: time.
η: viscosity of liquid.

If the penetration height is proportional to the penetration volume V, the equation becomes as follows for the same wood and liquid:

$$V = k\sqrt{t} \quad \cdots\cdots\cdots\cdots(2)$$

k: constant.

The penetration volume is proportional to square root of the time. ITō[2] also follows this equation.

In this work, it is examined with the typical softwood species in Japan, SUGI and HINOKI, whether the liquid penetration into these woods having various moisture contents also satisfies the above formulae.

Tracheids are occupying the major part of softwood structure and are the leading element of liquid penetration[3)4)], and their lumina are connected each other through the bordered pit pairs. According to CôTÉ and KRAHMER[5], a suspension liquid passes through pit pairs but the carbon black particles are stopped by the pit membranes. Penetration volume is to be influenced by the dimension

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and number of pit pairs and the proportion of aspirated pit pairs. Thus the penetration of liquid is to become more difficult, when the thickness of test piece is over tracheid length, for not forming open tubes. By the way, WARDROP[6)7)] also recognized that the pits act an important role for liquid penetration both in sapwood and heartwood.

The proportion of aspirated pit pairs under oven dried and moistened conditions of wood is counted for checking connection with the penetrability.

Materials and Methods

For this experiment, the softwoods, SUGI (*Cryptomeria japonica* D. DON) and HINOKI (*Chamaecyparis obtusa* ENDL.), were used. In HINOKI, sapwood material

Table 1. Some properties of specimens.

Treatment	Species		Specific gravity in air dry	Annual ring width (mm)	Moisture content (%)
Oven dried	SUGI sapwood	A	0.331	3.48	0
		B	.361	2.78	0
	SUGI heartwood	A	.347	4.45	0
		B	.387	4.05	0
	HINOKI sapwood		.437	3.25	0
Air dried	SUGI sapwood	A	.341	3.00	15.0
		B	.339	3.17	13.9
	SUGI heartwood	A	.348	3.65	14.0
		B	.374	4.70	13.0
		C	.368	8.20	
	HINOKI sapwood		.468	3.85	14.9
Moisture saturated	SUGI sapwood	A	.326	3.88	23.6
		B	.350	2.63	26.8
	SUGI heartwood	A	.363	5.05	21.6
		B	.360	3.79	24.3
	HINOKI sapwood		.436	3.13	23.9

was taken from a trunk, but in SUGI, sapwood one from two trunks and heartwood one from three trunks as shown in Table 1. From normal and sound part of each material, test specimens, 2×2×4 (cm), were prepared and kept in the room.

The properties of the specimens are shown in Table 1. Due to the moisture content, the specimens were classified in three groups, that is in oven dried, air dried, and moisture saturated conditions. To get the oven dried specimens, they were dried enough for 48 hrs. at the temperature of 65°C and subsequently for 48 hrs. at 105°C. After oven drying, they were kept in a desiccator containing a little phosphorus pentoxide for 24 hrs. and thereafter penetration treatment was carried on in the same desiccator. To get the moisture saturated specimens, they were put in a desiccator prepared with distilled water, weighed frequently until the weight of each specimen showed constant value, and thereafter penetration treatment was carried on in the same desiccator. The temperature was kept at 26°C during the experiment.

Impregnating method of liquid for this experiment was as follows: a flat glass covered with a sheet of filter paper was placed on the bottom of a Petri's dish, and the paper was kept wet with 1% aqueous solution of acid fuchsin. Then, the specimens on the filter paper, one end grain surface of them just touched the wet paper. Four lateral surfaces of the specimens were coated with vaseline as thin as possible for preventing liquid rising on the surfaces, although the lateral surfaces essentially take no part in penetration from an end surface as reported by DOSTAL and MARRACCINI[8]. When the liquid penetration was quick in action and its head reached to another end surface of the specimen, this surface was also coated with vaseline. In this connection, ITŌ[9] reported that there was no effect in heartwood but a little in sapwood of coating opposite end surface. ENOMOTO et al.[10] showed the influence on penetration of air contained in wood. From the result of our preliminary test, the effect of vaseline coating for obstructing penetration was also scarce. Thus the purpose of the vaseline coating of this experiment was merely for preventing extention of fuchsin solution on the lateral surfaces of specimens. In fact, the vaseline penetrated only one or two cell layers into wood transversely and negligible effect for obstructing longitudinal liquid penetration. On the other hand, if paraffin be used instead of vaseline of this work, the coated surfaces will often be cracked by swelling stress of the specimen in absorbing water.

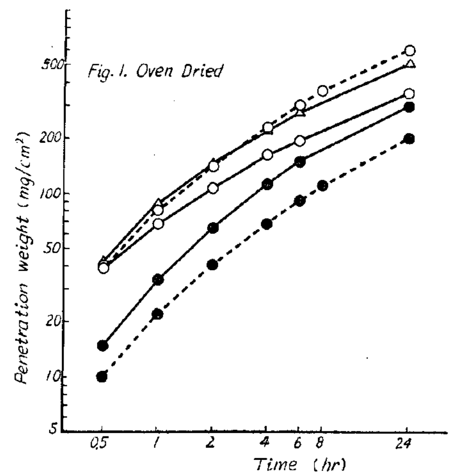
Weight of the specimens were measured in every 0.2, 0.5, 1, 2, 4, 6, 8 and 24 hr, and converted to per unit area. Of course, excess liquid were wiped with blotting paper from each specimen after taking it out from the Petri's dish. Thus the relation between penetration weight and time, and the average slope of penetration-time curve were obtained through 24 hrs. The specimens which had been assigned for above measurement were splitted into four pieces parallel to the ray tissue, and the condition of liquid penetration was catched as a photograph on each splitted surface. The penetration lengths were measured by the photographs at 20 points of every surface. Thus the relation between the penetration weights and lengths was obtained.

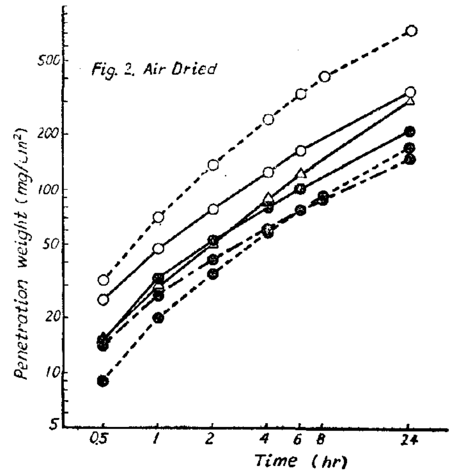
Then the splitted specimens showing average values of penetration were chosen for each treatment, and three sheets of cross section, 20μ thick, were cut from them by a sliding microtome and stained with ruthenium red. From these sections, the proportion of aspirated pit pairs were observed and counted in the earlywood tracheids.

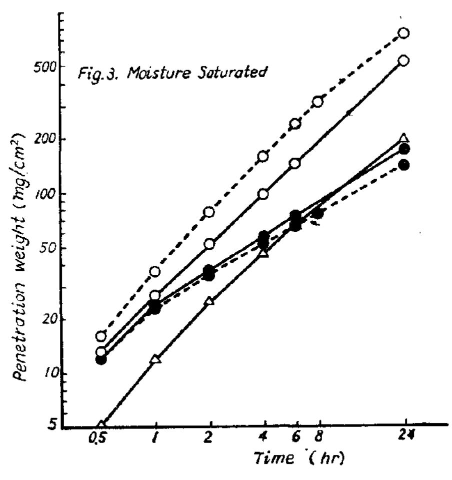
Results and Discussion

1. *Relation between Penetration and Time.*

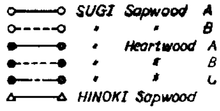
At the first twelve minutes of penetration, penetration weight, that is the weight of penetrated liquid, showed a considerable fluctuation caused by coarseness of







Figs. 1~3. Penetration weight-time curves of every moisture content.



penetrating surface of the specimen and by its contacting condition with the solution. Hence the penetration weight at every stage of 0.5~24 hrs. was converted on the basis of that at 0.2 hr, and relations between these penetration weights and times are shown in Figs. 1~3.

It is natural that the penetrability of sapwood was larger than that of heartwood in the every treatment as recognized by ERICKSON and BALATINECZ[11] for Douglas fir, but the difference between sapwood and heartwood of SUGI B was larger than that of SUGI A also in every treatment. It seems that this fact was not caused by the difference of treatments but the characteristics of individuals like Douglas fir having receptive and refractory woods according to KRAHMER[12].

The penetration weight for SUGI sapwood had no difference for the three groups of moisture content, but those of SUGI heartwood and HINOKI sapwood showed some difference. The oven dried specimens were more penetrable and the moisture saturated ones were less penetrable, than the air dried ones. This result is resembles to ITŌ's one[13]. As to the oven dried specimens, difference between sapwood and heartwood penetration grew smaller, and as to the moisture saturated specimens, it grew larger with the lapse of time. The value of average slope of penetration-time curve v was derived from the following equation:

$$\log W = v \log T \qquad \cdots\cdots(3)$$

W: penetration weight.
T: penetration time.

The values of v are shown in Table 2.

While the slope of heartwood in oven dried specimens was steeper than that of sapwood, the slope of sapwood in moisture saturated specimens was steeper than that of heartwood. In view of this fact, it will be suspected that the oven dried specimens of sapwood having larger initial penetrability will be outrun by

Table 2. The value of average slope of penetration-time curve.

Species \ Treatment		Oven dried	Air dried	Moisture saturated
SUGI sapwood	A	0.59	0.69	0.94
	B	.71	.82	1.00
SUGI heartwood	A	.80	.63	.64
	B	.77	.74	.58
	C		.55	
HINOKI sapwood		.65	.79	.96

the moisture saturated specimens of sapwood in the case of continuing this condition. In fact, ERICKSON and CRAWFORD[14] recognized the effect of air seasoning on penetrability, and reported that the penetrability of the specimens which were mildly dried was about 50% higher than that of specimens which were fast dried.

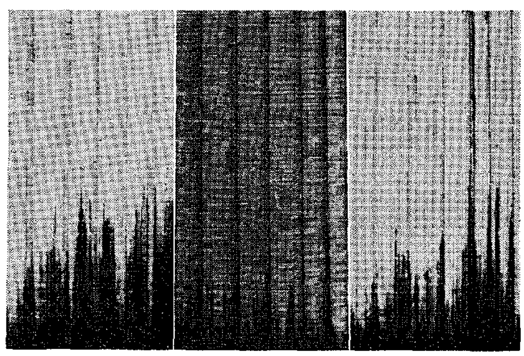
Proportional relation between penetration weight and time concerning the moisture saturated sapwood of SUGI and HINOKI is shown in Table 2. The value of slope, nearly 0.5, shows the proportional relation between penetration weight and square root of time. The oven dried specimens of sapwood showed comparative small value of 0.6~0.7 and almost followed the theoretical formulae given by STAMM[1] and ITō[15]. The air dried specimens showed values of 0.7~0.8, the moisture saturated specimens showed values of nearly 1, and these can not follow above formulae since the materials have already been perfectly air dried. It seems that the value of slope was more intensively influenced by the difference of moisture content of specimens than by the structural change of pits or tori caused by the treatment.

In heartwood, difference of the value of average slope for each treatment could not be recognized, and even the specimen having especially wide annual rings had no difference of it comparing with that having normal rings.

As to the influence of specific gravity of wood, KUMAR[16] stated that a lighter material absorbed more liquid than a heavier one. From the Table 1 and 2 or the Figs. 1~3, the effect of specific gravity of the materials to the penetration is not clear. According to MILLER[17] and ERICKSON et al.[18], there was no influence of specific gravity or latewood proportion on the longitudinal penetration, and KORAN[19] also obtained the same result.

2. Relation between Penetration Length and Weight.

Generally, it seemed that the penetration occures deeply in latewood tracheids of narrower diameter but it did not mean intensive penetration, and accordingly, it may be stated that the maximum penetration could not be found in the latewood portion, but in middle part of the annual ring, as shown in Photo 1 for example.



SUGI sapwood SUGI heartwood HINOKI sapwood

Photo 1. Radially splitted surfaces showing penetration of acid fuchsin solution from the lower end surface.

BURO et al.[3] found that the penetrability of earlywood and latewood had little difference. So, between average penetration length L(mm) and weight W(g) consists of the following equation:

$$\cancel{W=aL}\quad L=aW \qquad \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

a : constant.

The value of a in the equation was calculated for each treatment concerning all specimens.

$$\left.\begin{array}{ll} \text{at oven dried state} & a=15.4 \\ \text{at air dried state} & a=19.5 \\ \text{at moisture saturated state} & a=21.9 \end{array}\right\} \qquad \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

Thus the penetration length L of moisture saturated specimens is to be about 30% longer than of oven dried ones. Difference of liquid into dried cell walls seems to be a reason of this fact.

3. Relation between Pit Aspiration and Penetration.

At the penetrating, liquid moved from tracheid to tracheid through the bordered pit pairs between them. If the pit aperture is closed by torus, liquid penetration would be obstructed. With a view of this fact, the aspirated pit proportion was counted for each treatment of both species and its results are shown in Table 3.

The average percentage of aspirated pit pairs in heartwood is generally larger than in sapwood, and that of dried specimens is larger than that of wet speci-

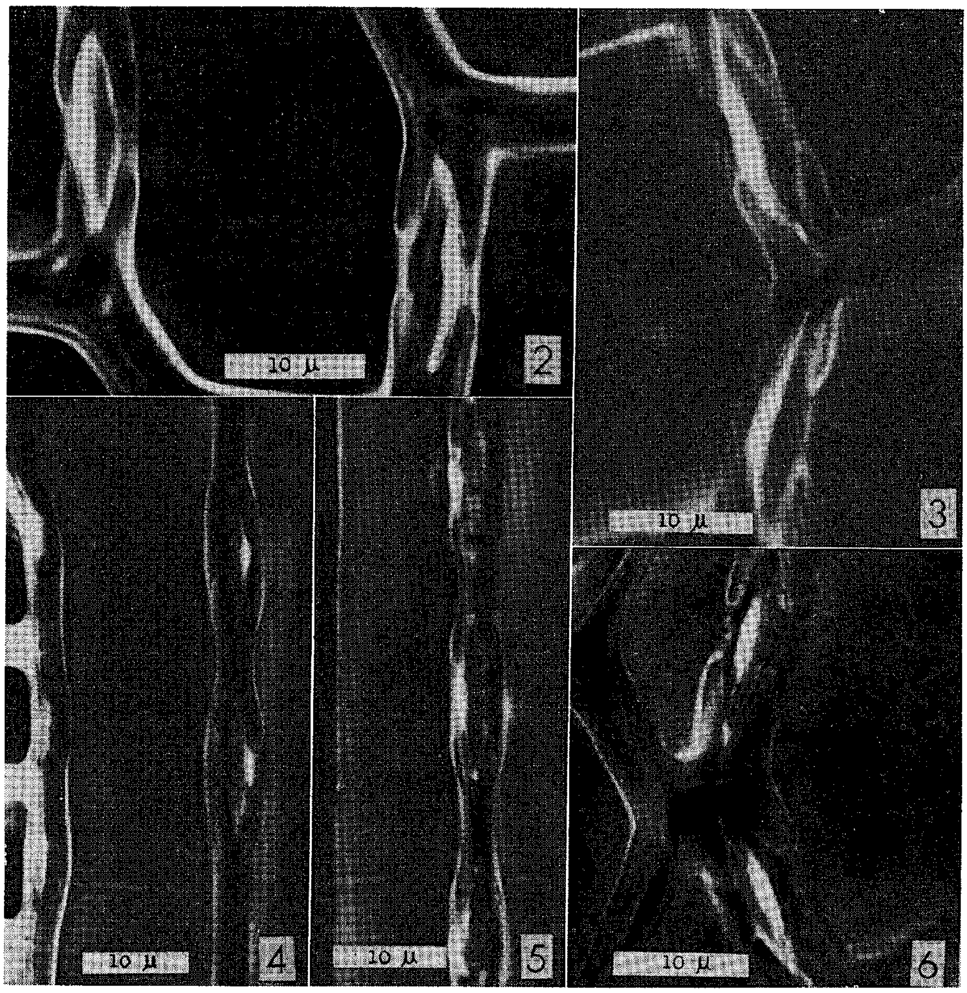
Table 3. Percentage of aspirated pits.

Treatment	Species	Annual ring														
		No. 1			No. 2			No. 3			No. 4			Average		
		Section														
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Oven dried	SUGI sapwood A	81	79	76	67	75	70	67	69	68	74	77	72	72	74	71
	SUGI heartwood A	85	85	85	42	43	44	86	89	80	60	58	57	77	76	74
	HINOKI sapwood	71	73	72	70	63	71	77	77	72	68	70	74	72	72	72
Air dried	SUGI sapwood A	63	54	56	65	66	70	61	65	58	66	64	68	63	62	61
	SUGI heartwood A	64	63	62	75	76	74	67	57	68	79	80	78	73	72	71
	SUGI heartwood C	73	80	74	58	66	65							63	70	67
	HINOKI sapwood	68	69	69	61	65	68	78	84	84	63	61	60	68	70	69
Moisture saturated	SUGI sapwood A	22	26	14	43	38	48	72	68	64	47	48	52	43	42	43
	SUGI heartwood A	73	75	71	74	75	70	77	74	78				75	75	73
	HINOKI sapwood	40	39	49	40	45	36	44	43	42	71	70	73	48	49	48

mens. These results correspond to those of ERICKSON and CRAWFORD[14]. The counted pit pairs were totally 14,610 entirely in earlywood, but the proportion of aspirated pit pairs of latewood seems to be smaller than that of earlywood[20]. But, from Table 3 and Figs. 1~3, it is not clear whether the proportion of aspirated pit pairs influences on the penetrability.

In Table 3, it is interesting that the proportion of aspirated pit pairs obtained from the same annual ring has nearly same value even in different sections. But the average proportion of aspirated pit pairs for each annual ring are different each other.

Therefore, to count the proportion of aspirated pit pairs, it is desirable to prepare sections of specimens containing more annual rings instead of preparing a number of sections. From Photos 2~6, it is found that, as to a certain tracheid, the situation of pit, i.e. aspirated or opened, is same.



Photos 2~6. Negative micrographs showing pit aspiration. (Photos 2, 3, 6 : *x*, 4, 5 : *t*)
Among these pit pairs, the unaspirated, opened ones are seen only in Photo 6.

Conclusion

(1) The influence of moisture contents on the penetration was not clear in SUGI sapwood, but, as to the SUGI heartwood or HINOKI heartwood, the penetration was large in oven dried state, medium in air dried one, and small in moisture saturated one.

(2) The value of slope of penetration-time curve in 24 hrs was larger of heartwood than of sapwood in oven dried wood, but of sapwood than of heartwood in moisturte saturated wood. As to moisture saturated sapwood, the fact having approximately 1 of the value of slope shows that the penetration is in proportion to time.

(3) It was found that, penetrating the same amount of liquid, the penetration length was about 30% longer in moisture saturated wood than in oven dried wood.

(4) Proportion of the aspirated pit pairs was larger in air dried wood than oven dried one, but its influence on the penetration was not clear. The proportion was nearly similar in the same annual layer although the observed sections were different.

摘　　要

供試材にスギ辺材 (A, B), 心材 (A, B, C) およびヒノキ辺材を用い, 含水状態は絶乾, 気乾および飽湿の3段階とした (Table 1)。

酸性フクシン1%水溶液を長軸方向に浸透させ, 時間と浸透量との関係を調べた (Figs. 1～3)。

スギ辺材では浸透に及ぼす含水率の影響が明らかでなかつたが, スギ心材やヒノキ辺材では, 浸透は絶乾材に大きく, 気乾材で中庸, 飽湿材では小さかつた。

スギ辺材の浸透は心材のそれより大きかつた。辺材と心材との浸透量の差がスギAよりBの方が大きいのは樹木個性によるものであろう。

時間と浸透量との両対数グラフから得た平均傾斜の値 (Table 2) は絶乾材では辺材より心材の方が大きく, 飽湿材では辺材が大きかつた。したがつてこの状態で浸透が進めば, 最初に浸透の大きかつた絶乾辺材も, やがては飽湿辺材に追い越されるだろう。飽湿辺材で傾斜の値がほぼ1であることは, 浸透量が時間に比例することを示している。

浸透量が浸透長に比例するとして, その定数を求めると (5) 式のようになつた。すなわち同じ量だけ浸透した場合, 飽湿材では絶乾材より約30%浸透長が大きくなる。

各樹種別, 含水率別に平均的な浸透を示した試片から木口切片をとり, 早材仮道管の約15,000個の膜孔についてトールスの位置を観察し, 閉鎖膜孔率を求めた (Table 3)。乾燥材あるいは心材では閉鎖率が大きかつた。細胞間の通路としては膜孔対のみしか考えられないところから, 浸透には閉鎖率が多少とも影響していると思われるが, はつきりした結論は下せない。ただ切片が異なつても, 同一の年輪層における膜孔閉鎖率がほぼ等しい値を示していることを知る。これは1本の仮道管において, ある膜孔が閉鎖していると, その仮道管の他の膜孔も閉鎖していることが多いのを示しているとも解せられる (Photos 2～6)。

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